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The use of focused current beams for electrical logging of boreholes is known and in the specification of British patent No. 833990 published May 4, 1960 there is described a borehole dipmeter which makes use of three such beams for obtaining electrical logs along three profiles of a borehole, which logs can, in conjunction with other information, be used in known manner for determining the angle and azimuth of dip of strata traversed by the borehole. A focused current beam may be obtained by using a logging electrode in the form of a relatively small, electrically conductive area in the surface of, but insulated from, a relatively large elongated electrode maintained at the same or substantially the same potential as the logging electrode. The relatively large elongated electrode is preferably cylindrical in shape, the logging electrode being situated in its outer surface, but it may be any other shape which enables a focused beam of current to be emitted from the logging electrode. The logging electrode is usually called a "beamed current electrode" and the elongated electrode is usually called a "guard electrode".

It is an object of the present invention to provide a method of and apparatus for logging boreholes which can produce a visual representation of a borehole wall. Such a representation is useful for many purposes; for example it can be used for determining the angle and azimuth of the dip of geological strata traversed by the borehole.

According to the invention, there is provided a method of logging a borehole which comprises running a logging sonde along a borehole containing a conducting fluid, scanning a substantial proportion of the area of the borehole wall past which the sonde moves by means of one or more narrow focused electric current beams emitted from the logging sonde, the said substantial proportion of the area of the borehole wall being substantially evenly distributed around the wall, and recording the variations in the intensity of the current caused by variations in the resistivity of the strata past which the sonde travels, in the form of a visual representation of the borehole wall.

The expression "conducting fluid" is meant to include any fluid which is capable of transmitting the current beam satisfactorily. Drilling fluids are sufficiently conductive for the purpose in question.

The said substantial proportion of the area of the borehole wall should preferably be at least one third, especially at least two thirds, of the total area of the borehole wall past which the sonde moves and it may of course be the whole area.

According to the invention furthermore, there is provided apparatus for logging a borehole, comprising a logging sonde having an elongated guard electrode and one or more beamed current electrodes, the said beamed current electrode or electrodes being adapted to emit a narrow focused current beam or beams of electric current and being so arranged that when running the sonde along a borehole containing a conducting fluid a substantial proportion of the area of the borehole wall past which the sonde moves is scanned by the current beam or beams, and means for recording variations in the intensity of the current beam or beams caused (in the use of the instrument) by variations in the resistivity of the strata past which the sonde travels, in the form of a visual representation of the borehole wall.

According to one embodiment, the sonde has at least one beamed current electrode which is adapted to be rotated so as to scan a spiral track on the borehole wall in the use of the instrument.

According to another embodiment, the sonde is formed with at least one set of eight or more beamed current electrodes spaced around the outer surface of the guard electrode in a plane perpendicular to the axis of the guard electrode, and commutating means are provided for enabling the current leaving each beamed current electrode to be measured in turn. Advantageously the commutating means are located in or in proximity to the sonde in which case it is not necessary to have separate conductors for conveying the current signals from each beamed current electrode to the surface of the ground. The effect of measuring and recording the current leaving each of the beamed current electrodes in turn is, in the use of the instrument in a borehole, to obtain a resistivity log along a spiral track on the borehole wall.

The beamed current electrode or electrodes should be sufficiently small and the beams sufficiently focused to make it possible to detect strata junctions as small as 1/16 inch thick. This is possible with a beam which is no more than about 0.6 inch thick in a vertical direction at the point where it intersects the borehole wall. Preferably no dimension of the faces of the beamed current electrodes should exceed half an inch. Most suitably the beamed current electrodes are square or circular in cross-section, the diagonal or diameter being 0.3 inch or less. Where the electrodes are square, best results are obtained when the diagonals of the square are horizontal and vertical (assuming the elongated guard electrode to be vertical). In the embodiment using eight or more beamed current electrodes, the number of electrodes should preferably be sufficient to ensure that at least one third of the borehole wall past which the sonde moves is covered by the measuring beam. For this purpose, it is necessary that at least one third of the surface of the sonde along a line passing through the centres of the faces of the beamed current electrodes should be constituted by the faces of the beamed current electrodes. Thus in the case of a sonde in the form of a right circular cylinder of 3" diameter having beamed current electrodes 0.3" across in a horizontal direction, the number of beamed current electrodes should preferably be at least 10.

The commutating means may be mechanical or electronic. For example it may comprise a rotary switch so constructed that, at any given instance, all but one of the beamed current electrodes are connected directly to the guard electrode, the remaining electrode being connected to the guard electrode via the primary winding of a transformer whereby the current leaving that electrode may be measured.

The purpose of the guard electrode is to focus the beams of current emitted by the beamed current electrodes, i.e. prevent their diverging too rapidly after leaving the sonde. A convenient shape for the guard electrode is a right circular cylinder in the outer surface of which the beamed current electrodes are situated. For most logging

ations carried out in oil wells or boreholes drilled during the search for oil, a guard electrode of this type having a diameter of from 2-6 inches would be suitable. With this arrangement, the spread of the current beam from a beamed current electrode in a horizontal plane when the assembly is suspended in a borehole is purely determined by the angle subtended at the axis of the guard electrode by the beamed current electrode. On the other hand, its spread in the vertical plane depends not only on the length and shape of the guard electrode but also on the relative resistivities of the media encountered by the beam.

For the purpose of examining the borehole wall, it is desirable that the current beam should diverge as little as possible while passing through the borehole fluid and that it should diverge rapidly after it strikes the borehole wall. Such a shape ensures that most of the resistance offered to the current beam occurs at the borehole wall. A shape of this type is normally obtained when the diameter of the guard electrode is 1/4 to 1/2 that of the borehole being logged and the overall length of the guard electrode 1/2 to 5 times the borehole diameter in the case of a simple circular cylindrical guard electrode and beamed current electrodes not more than 1/2" across in any direction. However, it may be advantageous in some circumstances to focus the beam so that it remains concentrated for some distance into the formation. The final picture obtained with this arrangement would be of the formations behind the borehole wall rather than of the borehole wall itself and references in this specification to visual representations of the borehole wall should be taken to include also visual representations of the formations behind the borehole wall.

Adjustment of the focusing of the current beam may be obtained if desired in various ways. For example, the guard electrode may be provided with an hour-glass waist in which the beamed current electrodes are situated. By this means, additional focusing of the current beams may be obtained. Also, the guard electrode surface may be split into more than one piece and the potentials of the various pieces or the

flowing from them may be adjusted slightly so as to provide additional focusing of the current beams emitted by the beamed current electrodes. For example, each beamed current electrode may be surrounded by a subsidiary ring-shaped guard electrode maintained at a slightly different potential from the main guard electrode.

The current measurements from the beamed current electrodes or electrode may be recorded or displayed by a variety of means. In one method of obtaining a permanent record, the current signals are used to intensity-modulate a trace described on the screen of a cathode ray oscilloscope, the time base of the oscilloscope being synchronised with the rotation of the current beam or with the commutating means so that each sweep of the trace represents a 360 degrees rotation, means being provided for obtaining a continuous photographic record of the oscilloscope display.

Advantageously the current signals may be displayed on a cathode ray oscilloscope screen so that a resistivity picture of the interval just logged may be viewed there, this picture moving as the sonde is moved in the hole. This display may be achieved, for example, by recording the current signals continuously on a magnetic memory drum using a writing head driven by motion of the cable connected to the logging sonde so that the writing head makes one revolution of the drum for each unit of distance (e.g. twenty feet) moved by the sonde. The memorised signals are then read continuously by a reading head rotating round the drum synchronously with the movement of the cathode ray spot over an oscilloscope screen in a manner essentially similar to that used in a television receiver, the memorised signals intensity-modulating the cathode ray spot. Incorporated with the memorised current signals would be means providing line synchronisation of the cathode ray spot with rotation of the current beam in the borehole, or with the commutating means, as the case may be, each line on the displaying oscilloscope screen corresponding to 360 degrees rotation, and means providing frame synchronisation of the oscilloscope display such that a new frame would be started each time the reading head on the magnetic drum passed the writing head on the magnetic drum.

Methods of display giving a visual presentation of the borehole wall without the aid of a cathode ray oscilloscope are also possible.

One such method is to employ a sensitised paper recorder of the type commonly employed for marine echo sounding. The sensitised paper reacts to the intensity of current passed through it from a moving stylus, the stylus speed across the paper being synchronized with the rotation of the current beam or to the commutating means and the paper speed to the logging speed and the stylus being fed with a voltage proportional to the signal from the beamed current electrode or electrodes. Means may advantageously be provided for indicating a reference direction on the record.

Another method would be to feed the signals from each one of the beamed current electrodes (amplified and modified as required) to an independent indicator, the illumination of which is proportional to the signal received. The indicators are positioned in a pattern corresponding to the positions of the beamed current electrodes on the guard electrode and a permanent record may be obtained, as for the cathode ray display, on film moving across the indicators in step with the movement of the instrument in the hole. This type of display could be used with or without a scanning type of operation and is particularly suitable where the sonde is provided with more than one set of eight or more beamed current electrodes arranged as described above.

In all the above techniques for obtaining a permanent record it is advantageous to provide in association with the sonde, a north-seeking device, or the like, having electrical connections so arranged that a reference direction is indicated on the final record. By this means it is possible to obtain an oriented picture of the borehole wall. For example, where a cathode ray oscilloscope is used for obtaining the record, the electrical connections may conveniently be arranged so that the initiation of the time base of the oscilloscope is at magnetic north.

The apparatus according to the invention may be used for carrying out dipmeter surveys of boreholes. For this purpose it is necessary to use in conjunction with the logging sonde, an inclinometer, which may be of any known kind, for determining the orientation of the sonde relative to vertical and a fixed reference direction, e.g. magnetic north. The inclinometer described in British patent No. 838061 published June 22, 1960 is a particularly suitable one to use.

One embodiment of the invention will now be described by way of example with reference to the accompanying drawings in which

Figure 1 is a vertical section through part of the electrode assembly in a borehole,

Figure 2 is a horizontal section along the line A-A of figure 1,

Figure 3 is an elevation of the sonde in position in a borehole,

Figure 4 shows, in simplified form, a suitable electrical connection between the electrode assembly and the surface of the ground.

Figure 4A shows a type of recording system that can be used with the invention, and

Figure 5 shows, diagrammatrically, a section of borehole and the records obtained when logging it with the apparatus according to the invention.

Referring first to figures 1 - 3, there is shown a logging sonde 10, comprising a potential guard electrode 11 in the form of a hollow right circular cylinder, and twenty beamed current electrodes 12 insulated from the potential guard electrode by means of insulating material 13. The sonde is shown in a borehole 14 filled with drilling fluid 15, the sonde being centralised in the borehole by means of bowsprings 16 attached to non-conducting extensions 17. For the sake of simplicity, the electrical connections to the electrodes have not been shown in figures 1 - 3.

The beamed current electrodes are square in cross-section, the diagonals of the squares being horizontal and vertical. The relative sizes of the guard and beamed current electrodes are such that two thirds of the surface of the sonde along a line passing through the centres of the faces of the beamed current electrodes is constituted by the faces of the beamed current electrodes. With this arrangement it is possible to scan at least two thirds of the wall of a borehole.

Referring now to figures 4 and 4A, current at 60 c.p.s. is supplied from the surface of the ground along the conductor 18 of a cable 19. The current is fed via a current stabiliser 20 to the guard electrode (not shown). A transformer 21 provides H.T. and L.T. power for the subsurface equipment. A rotary switch 22 which includes a rotor member 22a and a ring of stationary commutator segments 22b connects each beamed current electrode in turn to the guard electrode via contact brushes 22c and 22d the low impedence primary winding of a transformer 23 and conductor 24. All the other beamed current electrodes are connected directly to the guard electrode via brushes 22e, brush 22f and conductor 25. The rotary switch 22 is driven by a motor 31. The signals from the beamed current electrodes are fed via an amplifier 26 and a telemeter and buffer network 27 back up the cable 19 by way of a second conductor 18a. The frequency of these signals is altered in network 27 so that there will be a minimum of interference from the power supply current. A relatively simple and well-known type of frequency changer which may be used for this purpose consists of a rectifier and filter circuit for converting the a.c. signals to d.c. signals.

The signals from the beamed current electrodes are used to intensity-modulate a cathode ray oscilloscope 32 at the surface of the ground. The time base circuit 33 of the oscilloscope is synchronised with the rotary switch 22 and to this end, operates in a well-known manner to recognize the signal discontinuity that occurs when the brush 22c contacts the unconnected ones of the commutator

segments 22b. In use, a continuous photograph of the oscilloscope trace 34 is taken on a film 35 which is moved across the trace in step with the vertical movement of the sonde up the borehole. A typical record is shown diagrammatically in figure 5 (b) aligned with a diagrammatic representation of the appropriate section of the borehole 5(a). Thus, when the current beam enters high resistivity (low conductivity) strata 28, the beam current intensity falls, giving a low intensity on the oscilloscope 32, which reproduces a lower intensity on the final photograph, and vice versa. This photograph is a resistivity representation of the stratigraphical sequence.

In order that the record can be used to determine the dip of the strata penetrated by the borehole, an inclinometer is used in conjunction with the sonde. The inclinometer described in British Patent No. 838061 is particularly suitable for this purpose since the voltage pulse produced as the search finger 24 of the inclinometer described in British Patent No. 838061 passes through magnetic north can be used to trigger the time base of the oscilloscope. This ensures that the record 5 (b) begins and ends at magnetic north as shown. The inclinometer also provides a continuous record of the angle of inclination of the sonde with respect to the vertical and of the azimuth of such inclination. This record is shown in Figure 5 (c), and the records 5 (b) and (c) provide all the information required for determining the angle and azimuth of the dip of the strata.

In the use of the instrument, the rate of commutation should preferably be such that substantially full vertical coverage of the borehole wall by the measuring current beam is obtained at the particular logging speed being used. Assuming a logging speed of 500 feet per hour and a vertical coverage of half an inch, the beam rotation speed must therefore be at least one revolution in 0.3 seconds which requires a minimum rotational speed of 3 revolutions per second.

The main advantage resulting from the use of the method and apparatus according to the invention is that there is obtained a continuous visual display of the borehole wall or of the surrounding strata which can be studied and re-studied and directly interpreted by site geologists having no previous experience of dipmeter instruments as no computation work is involved.

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It will be appreciated that although reference has been made throughout the specification to recording variations in the intensity of the current beams, variations in any electrical characteristic of the electrical circuits associated with the sonde which are related to variations in the nature of the formations being logged may be used to obtain the visual representation of the borehole wall.

Instead of using a sonde in which the beamed current electrodes are set in the main body of the sonde itself, it is also contemplated that a visual representation of the borehole wall may be obtained using logging electrodes supported by pads applied against the borehole wall by means of springs, the electrodes being approximately in the same plane perpendicular to the axis of the borehole. Measurements from the electrodes may be commutated as described previously. With this arrangement it is not essential that the current emitted from the electrodes be focused. Each electrode may be supported in a separate pad or several electrodes may be supported in the same pad. The number of logging electrodes should preferably be at least eight and there may be several sets of electrodes arranged as described.

THE EMBODIMENTS OF THE INVENTION IN WHICH AN EXCLUSIVE PROPERTY OR PRIVILEGE IS CLAIMED ARE DEFINED AS FOLLOWS:

1. A method of logging earth formations traversed by a borehole comprising: measuring in sequence at a given level in the borehole the electrical resistance of portions of the formation material spaced around the circumference of the borehole; repeating the measurements at additional levels in the borehole; recording the various measurements at any given level in a sequential manner across a first dimension of a recording medium; and spacing the measurements for the different levels along a second dimension of the recording medium.

2. A method of logging earth formations traversed by a borehole comprising: measuring the electrical resistance of a small portion of the formation material adjacent a first point on the borehole wall; repeating this measurement at a succession of points around the circumference of the borehole; and displaying representations of these measurements in sequence one after the other to provide an indication of the horizontal cross-section of the adjacent formation region.

3. A method of logging earth formations traversed by a borehole comprising: measuring the electrical resistance of a small portion of the formation material adjacent a first point on the borehole wall; repeating this measurement at a succession of points around the circumference of the borehole while moving the level of measurement along the borehole in a longitudinal direction so that the measurements define a spiral track along the borehole wall; and recording representations of these measurements in a two-dimensional pattern to provide a developed or unfolded view of the formation material surrounding the borehole.

4. Apparatus for logging earth formations traversed by a borehole comprising: an elongated logging sonde adapted for movement through the borehole; a series of current emitting electrodes encircling the longitudinal axis of the sonde and supported by the sonde for movement therewith through the borehole; the current emitting electrodes having a common current return electrode far removed from the current emitting electrodes; means for energizing the electrodes; commutating means for sequentially measuring the current emitted by the individual electrodes; and means for recording these measured current values.

5. Apparatus for logging earth formations traversed by a borehole comprising; an elongated logging sonde adapted for movement through the borehole; a series of at least eight current emitting electrodes encircling the longitudinal axis of the sonde and supported by the sonde for movement therewith through the borehole; the current emitting electrodes having a common current return electrode far removed from the current emitting electrodes; means for energizing the electrodes; commutating means for sequentially measuring the current emitted by the individual electrodes; and means for recording these measured current values.

6. Apparatus for logging earth formations traversed by a borehole comprising: an elongated logging sonde adapted for movement through the bore-

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a series of current emitting electrodes encircling the longitudinal axis of the sonde and supported by the sonde for movement therewith through the borehole; the current emitting electrodes having a common current return electrodes far removed from the current emitting electrodes; means for energizing the electrodes; commutating means for sequentially measuring the current emitted by the individual electrodes; and means for recording representations of these measured current values in a two-dimensional pattern to provide a developed or unfolded view of the formation material surrounding the borehole.

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17. Apparatus for logging earth formations traversed by a borehole comprising: an elongated logging sonde adapted for movement through the borehole; a series of electrodes encircling the longitudinal axis of the sonde and supported by the sonde for movement therewith through the borehole; means for energizing the electrodes; commutating means for sequentially measuring the current emitted by the individual electrodes; recording means having a movable recording medium, a recording element which is adapted to produce a trace across the recording medium at right angles to the direction of movement thereof and means for controlling the intensity of the recorded trace; means for controlling the intensity control means in accordance with the measured current values; means for driving the recording element in synchronism with the commutating means so that each recorded trace corresponds to a complete commutating cycle; and means for moving the recording medium in synchronism with the movement of the logging sonde through the borehole.

8.

8. Apparatus for logging earth formations traversed by a borehole comprising: an elongated logging sonde adapted for movement through the borehole and including an elongated cylindrical guard electrode and a series of smaller electrodes supported intermediate the longitudinal extremeties of the guard electrode and encircling the longitudinal axis of the sonde; means for energizing the electrodes; commutating means for sequentially measuring the current emitted by the individual ones of the series of small electrodes; and means for recording these measured current values.

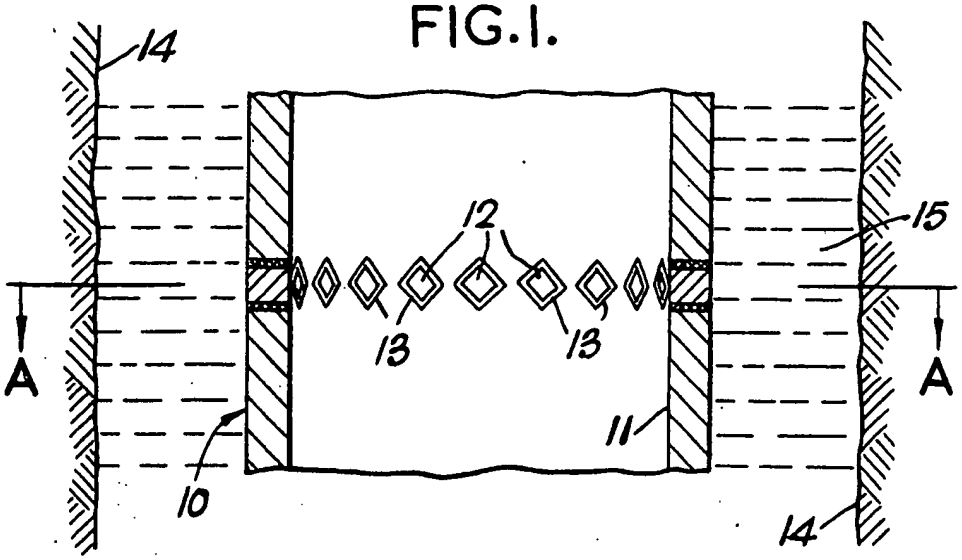
9.

~~10.~~ Apparatus for logging earth formations traversed by a borehole comprising: an elongated logging sonde adapted for movement through the borehole and including an elongated cylindrical guard electrode and a series of at least eight smaller electrodes supported intermediate the longitudinal extremities of the guard electrode and encircling the longitudinal axis of the sonde; means for energizing the electrodes; commutating means for sequentially measuring the current emitted by the individual ones of the series of small electrodes; and means for recording these measured current values.

10.

11. Apparatus for logging earth formations traversed by a borehole comprising: an elongated logging sonde adapted for movement through the borehole and including an elongated cylindrical guard electrode and a series of smaller electrodes supported intermediate the longitudinal extremeties of the guard electrode and encircling the longitudinal axis of the sonde; means for energizing the electrodes; commutating means for sequentially measuring the current emitted by the individual ones of the series of small electrodes; and means for recording representations of these measured current values in a two-dimensional pattern to provide a developed or unfolded view of the formation material surrounding the borehole.

FIG.1.



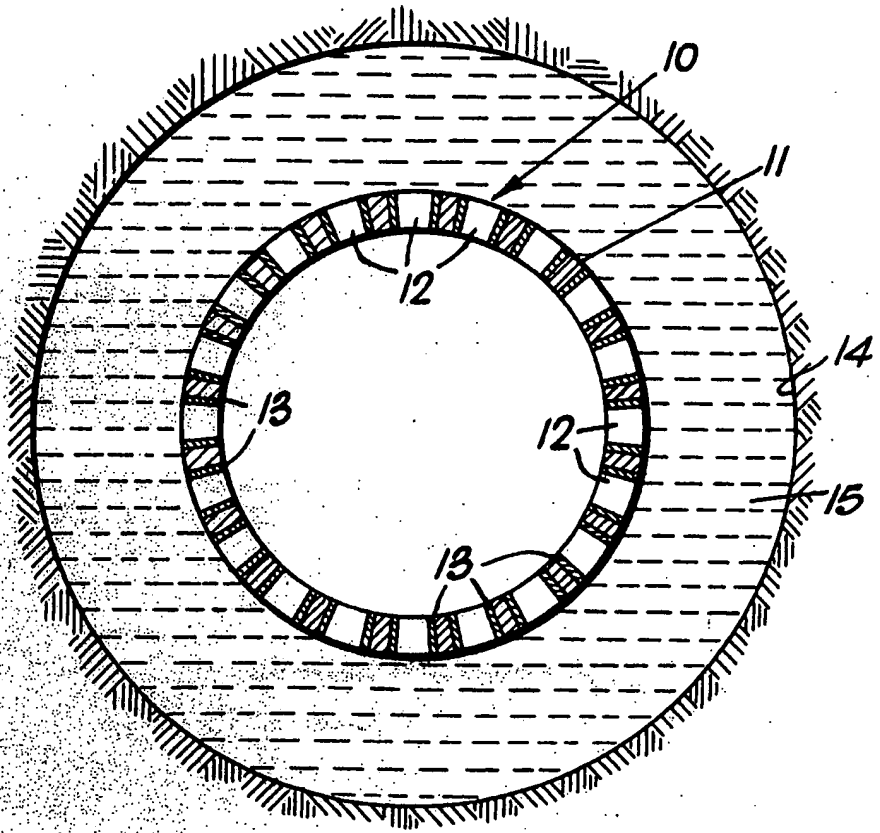


FIG.2.

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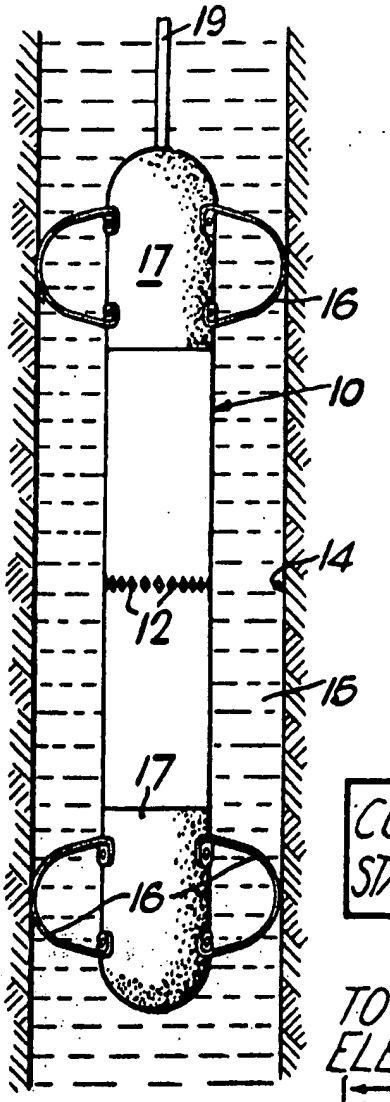

FIG. 3.

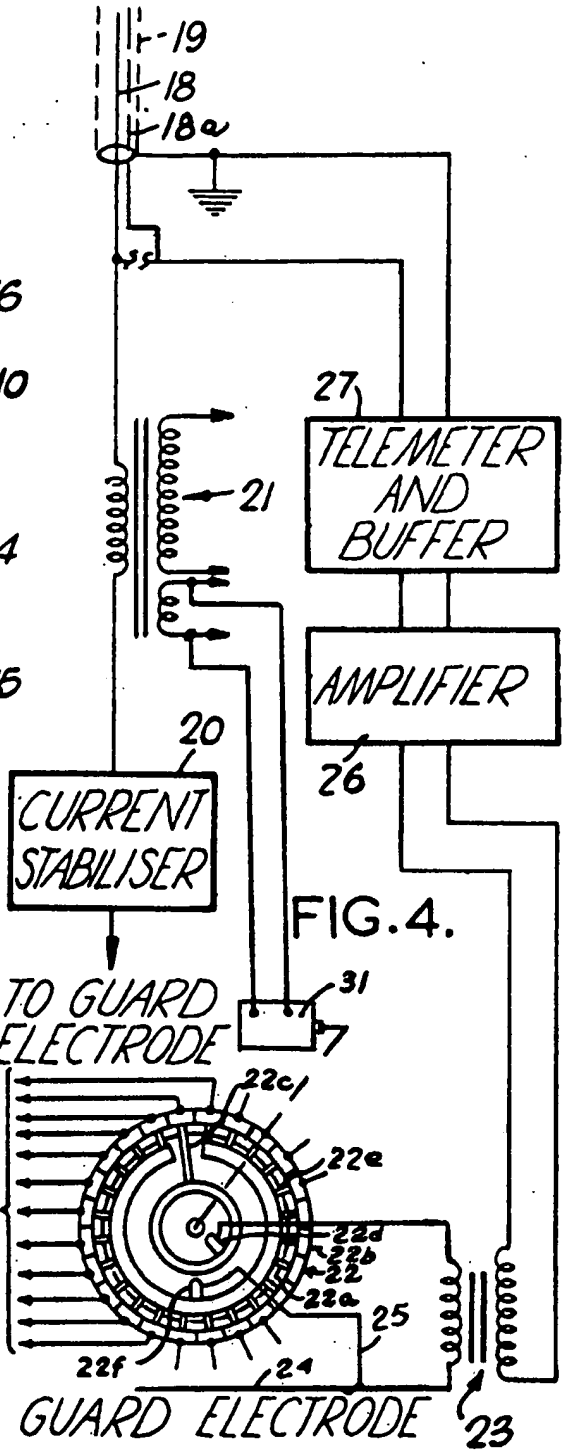

FIG. 4.

TO BEAMED CURRENT ELECTRODES

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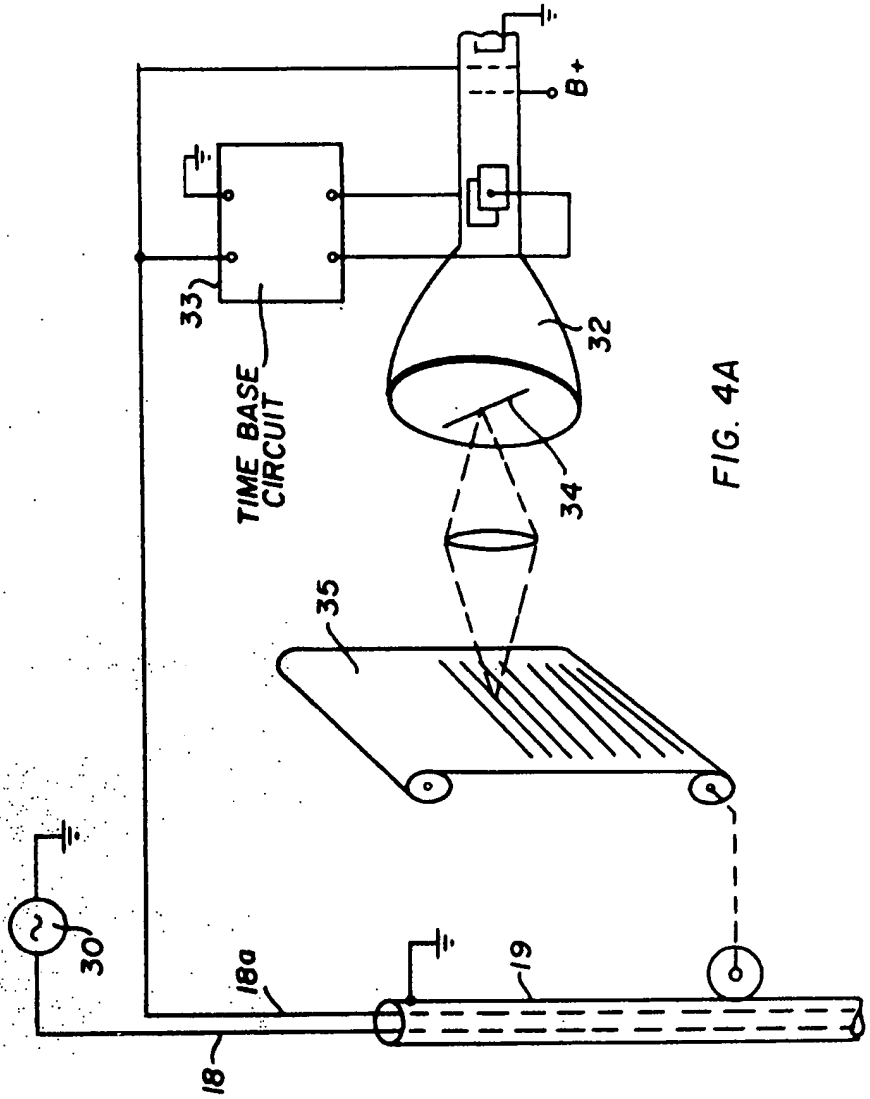

FIG. 4A

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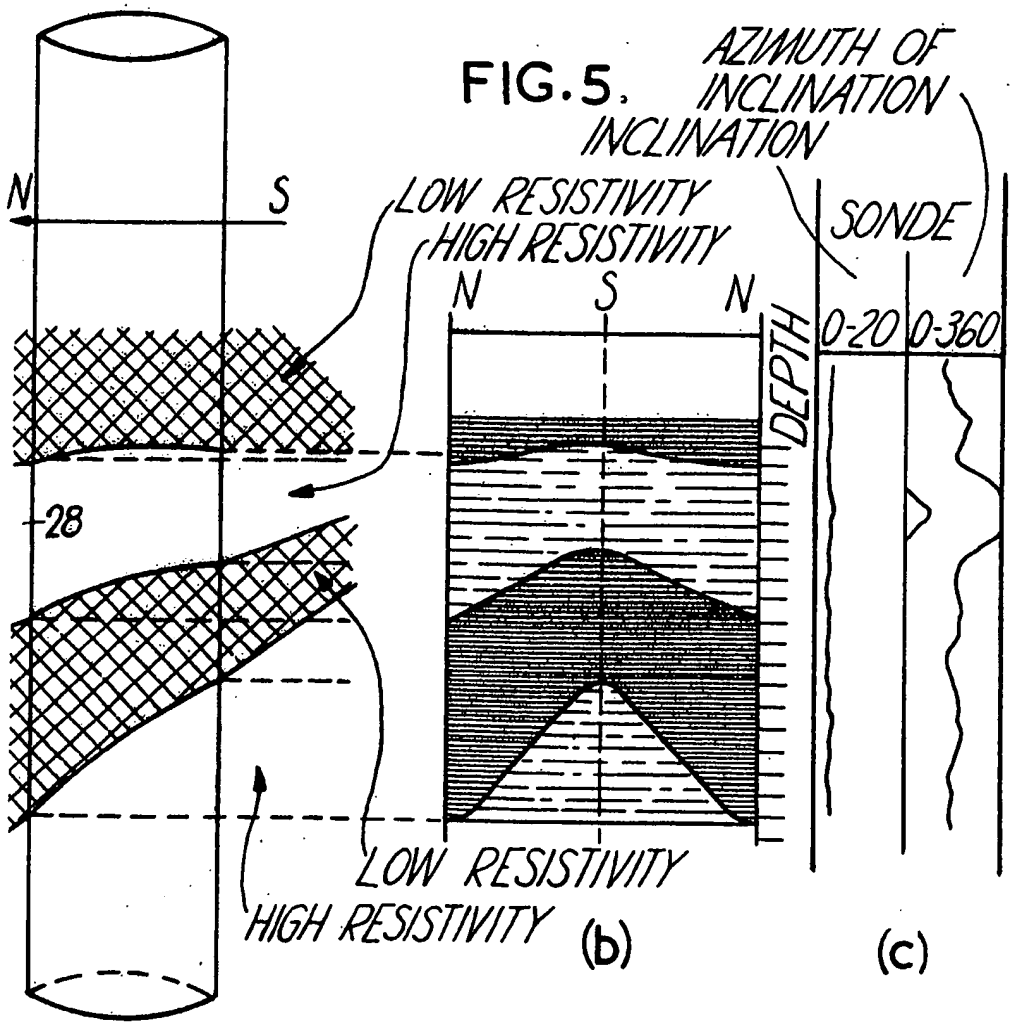
FIG. 5.



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